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PULSED GAS METAL ARC WELDING DEVELOPMENT-ALL-POSITION MANUAL PIPE WELDING

Report No 87-323-K

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ABSTRACT

This report describes the results of pulsed gas metal arc welding (P-GMAW) development work, conducted during 1986-1987 toward the qualification of a manual all-position carbon steel pipe welding procedure, which will satisfy the stringent acceptance criteria of lack-of-fusion defects. The possible causes for these defects were systematically evaluated in this program, and a suitable welding technique was developed for producing high integrity all-position pipe welds. It was concluded that the smoothness of the prior deposited layer's surface geometry is critical for obtaining defect-free welds. In addition, a full weave technique at a low current level is essential for all-position pipe welding.

job	file	date	report no.
81-143-500	823.11	April 22, 1988	87-323-K

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EXECUTIVE SUMMARY

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Gas metal arc welding (GMAW) has the advantage of high deposition rate and adaptability to mechanization when compared to the popular shielded metal arc welding (SMAW) process. The conversion from the SMAW to the GMAW process has been slow in the metal fabrication industry mainly due to the GMAW's susceptibility to fusion defects, and its inability to weld out-of-position when welding in the high deposition (spray) mode. Recent advances in pulsed-current gas metal arc welding (P-GMAW), however, have made this process a viable alternative to SMAW.

The present report provides a review of the P-GMAW work performed at OHRD to date towards the development of a manual all-position carbon steel pipe welding procedure that will satisfy the stringent acceptance criteria of nuclear piping. The main objective of this program was to systematically evaluate the possible causes of the lack-of-fusion defects which have plagued the previous attempts, and to develop a solution such that this technology can be applied in the field for piping installation, maintenance and repair.

It was determined that lack-of-fusion defects similar to those found in previous qualification tests can be simulated by a combination of weld bead spacing and bead placement, while welding in the horizontal position. The easiest method to combat fusion defects is to avoid the occurrence of deep and/or wide grooves between weld beads by proper weld bead placement. Radiographic and ultrasonic quality welds can easily be produced using the stringer technique when an average current of 140 to 160A is applied; however, a weaving technique using a minimum current of 110A has to be employed for all-position pipe welding when the vertical-up progression is involved. Appropriate welder training has proven to be one of the most important requirements for obtaining high quality pipe welds. An all-position pipe welding procedure has since been qualified, and is approved for use by Ontario Hydro.

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PULSED GAS METAL ARC WELDING DEVELOPMENT -
ALL-POSITION MANUAL PIPE WELDING

1.0 INTRODUCTION

This report provides a review of the pulsed-gas metal arc welding (P-GMAW) work performed at OHRD to date towards the development of a manual all-position carbon steel pipe welding procedure that will satisfy the stringent acceptance criteria of nuclear piping/1/. The main objective of the program was to systematically evaluate the possible causes of the lack of fusion defects which have been found in previous work and to develop a solution, such that this technology can be applied in the field for piping installation.

The P-GMAW development program has been supported jointly by the Chemistry and Metallurgy Section of CNS and by Research Division for the past several years. A manual all-position carbon steel pipe welding procedure has now been qualified, which brings to a successful conclusion an important phase of this development program.

2.0 BACKGROUND

Gas metal arc welding (GMAW) has the advantage of high deposition rate and adaptability to mechanization when compared to the popular shielded metal arc welding (SMAW) process. Although GMAW has been widely used in the metal fabrication industry, the conversion from the SMAW process to the GMAW process has been slow, mainly due to reasons such as the frequent occurrence of fusion defects usually associated with the short-circuiting transfer mode, and the inability to weld out-of-position when welding in the spray transfer mode. Pulsed-current GMAW are capable of welding out-of-position in the spray transfer mode without the high heat input and large weld pool that limits conventional spray transfer GMAW to the flat position. The ability to weld in the spray mode also minimizes the susceptibility to side wall fusion defects.

The major drawback of early P-GMAW systems is the difficulty involved in parameter setup, which seriously impeded the generalization of the process. Recent advances in transistorized power sources enable high frequency square wave pulsing for closely controlled metal transfer. With the development of 'one knob' power supplies that are designed with the 'one drop per pulse' control logic which automatically dictates the optimum pulse parameters for specific wire/gas combinations, and the addition of feedback systems that modulate transient responses to arc perturbations for maintaining the welding arc in a steady state, pulsed-GMAW has become a viable alternative to SMAW. The significance of this technology can easily be identified by the rapid increase in the numbers of P-GMAW power supply manufacturers over the last three years.

The Welding Unit of the Metallurgical Research Department has been conducting P-GMAW development work for the last few years. The majority of the welding tests were conducted using an Osaka Transformer Company (OTC) Transistarc 350 power supply purchased in early 1984. This machine is a 'one knob' control, frequency modulated unit that has preset programs for welding with carbon and stainless steel consumables. Subsequent purchase of the Hobart Quantum 350 and the OTC TRA350 power supplies had added both 'synergic control' and welding parameter programmability to the project. The effects of shielding gas mixtures and the ability to weld out-of-position were investigated during previous development programs. The ability to produce satisfactory welds in all positions led to the decision to concentrate program efforts on specific applications for field usage that can improve productivity and quality. The development of stainless steel welding procedures for overlaying of hydraulic turbine throat rings/2/ and for butt joining of Darlington fuel bay liners has proven to be highly successful. The latest effort in quantifying weld deposit geometry for in-situ robotic repair of hydraulic turbine runners has also revealed important insights toward the understanding of the P-GMAW process/3/. Preliminary testing with carbon steel also appeared to be promising, leading to attempts to qualify welding procedures for pressure boundary applications. It was during these tests that the serious nature of the lack-of-fusion defect problem became apparent.

The work program addresses the various approaches to eliminate the lack-of-fusion defect problem with special emphasis on all-position manual pipe welding. The program consists of five phases. These specific work areas are outlined below.

(1) Lack-of-fusion Simulation

(2) Power Source Response Characteristics

(3) Welding Consumable Evaluation

(4) Pulse Parameter Evaluation

(5) Welding Technique Development and Manual Procedure Testing.

3.0 LACK-OF-FUSION DEFECTS

3.1 Observed Occurrence

In an attempt to qualify a procedure for the repair of BHWP towers, lack of interbead fusion defects were observed in a manually welded temper-bead procedure qualification coupon. The coupon was welded in the horizontal position by field welders from BHWP. A cross-section of the specimen is shown in Figure 1.

Lack-of-fusion defects were also found during sectioning of manual pulsed-GMAW in-situ pipe welding trials performed by field welders using experimentally defined and optimized welding parameters. These defects occurred at random, regardless of welding position. The increase in heat input accomplished by manual weaving did not alleviate this problem.

The above defects were almost always found to contain entrapped slag, most likely consisting of oxides of Mn and Si, and were similar to those observed by other workers/4,5/.

3.2 Possible Causes Of Lack-of-Fusion Defects

It is very difficult to identify the exact cause of the lack-of-fusion defects associated with the process. Three major factors that are worth considering are process/procedure limitations, inadequate welding technique, and power supply deficiency. Some of the details are discussed below.

3.2.1 Process/Procedure Limitations

The typical penetration profile of spray mode GMA welds is of the deep finger type, with almost no secondary penetration near the weld toe. This makes the positioning of the weld bead with respect to the previously deposited metal very critical. If the spacing produced by the previously deposited bead is too wide which results in severly scallopped surface, the exact placement of the next bead will be crucial. This is especially true when out-of-position welding is involved, during which the sagging of the weld bead due to gravity tends to create cold lap defects.

Since it appears that the observed weld fusion line discontinuities are usually filled with slag, possibly oxides of Si and Mn, the amount of deoxidizer in the wire may be a contributing factor to the formation of the lack-of-fusion defect. The commonly used triple deoxidized ER70S-2 welding wire may serve to reduce the size of the bead placement tolerance box by promoting slag entrapment due to its high deoxidizer content.

3.2.2 Welding Technique

It is a well known fact that welder training is crucial for producing high quality short-circuit GMA welds. Special techniques have to be observed to avoid fusion defects. Welding technique is also likely to be a major issue in obtaining satisfactory P-GMA welds. Previous studies were all conducted using a mechanized system, so that the significance of the human variable was never fully assessed. It was definite that the development of a proper welding technique would be essential to the success of the program.

3.2.3 Power Source Characteristics

It is unfortunate that there is not a unified control logic that applies to all P-GMAW machines. Different manufacturers design their own control systems and develop their own welding programs; although, in most cases, the 'one drop per pulse' principle still applies. It is possible that the OTC Transistarc 350, which is a fixed program frequency modulated (FM) system, may not be entirely adequate for manual pipe welding applications. The inability to alter any pulse parameter to 'fine-tune' a procedure for specific applications may also be a hindrance in trying to achieve an optimum procedure.

The purchases of the Hobart Quantum 350 power supply, which is designed in accordance with the British Welding Institute 'synergic' P-GMAW concept, and the OTC TRA 350 programmable unit, have added the capability to investigate the significance of power supply design in the occurrence of lack-of-fusion defects.

4.0 WELDING EQUIPMENT AND MATERIALS

The majority of the welding trials were performed using an OTC Transistarc 350 power supply. This is a 'one knob' self-regulating power supply which has a control unit that automatically dictates the welding parameters for smooth metal transfer based on the type of filler wire and shielding gas selected. Peak pulse current (I_p), peak pulse duration (T_p), and low pulse current (I_b) are held constant during welding. A reference voltage which corresponds to arc length is set, and if the arc length changes during welding, the burnoff rate will be adjusted by varying the low pulse duration, thus restoring the preset voltage; this method of arc length control is termed 'frequency-modulated' control. On the other hand, the Hobart Quantum 350 power supply, which was used for the second phase of the testing, is a 'one knob' machine which modulates arc length variations using the British Welding Institute designed synergic logic. All the pulse parameters (I_p, I_b, T_p, T_b) float when burnoff rate changes, thus maintaining a stable arc, yet retaining the one drop per pulse characteristics. The third power supply, the OTC TRA350, is a frequency

modulated unit identical to the OTC Transistarc 350 with the exception that it is fully programmable. Parameters such as I_p, I_b, and T_p can be independently set, thus the ability to accommodate different wire/gas combinations is unlimited.

Travel speed was controlled by utilizing a KAT mechanized carriage system. Digital readout slides for torch-to-workpiece distance and lateral torch position adjustment were used to control torch location during the initial phases of the program. A custom built all-position fixture was used to perform the mechanized welding trials; this fixture can accurately duplicate different welding positions at 15^{o} intervals. The equipment is shown in Figure 2. Three water-cooled welding torches were also evaluated.

All the welding trials were performed with carbon steel plates and pipes of ASME P1 classification /6/. The majority of the welding was conducted using Ar/CO_2 gas mixtures and 0.9 mm diameter ER70S-3 welding wire.

5.0 WELDING TRIALS

A five-phase work program was initiated in 1986 for welding development in the manual pipe welding project/1/. Most of the work areas have now been addressed to some degree, as outlined below:

5.1 Lack-of-Fusion Simulation

Mechanized bead-on-plate tests were performed using an OTC Transistarc 350 welding power supply and its prefixed program for 0.9mm carbon steel wire with $80\%Ar/20\%CO_2$ as shielding gas. Average currents of 110A (vertical), or 170A (all other positions), and a travel speed of 6.35mm/s, were employed. Welding trials were performed in the horizontal, overhead and vertical positions. These trials were further divided into three stages, as summarized below:

5.1.1 Bead Spacing and Groove Geometry Determination

Bead-on-plate tests were performed with interbead spacings varying from half-bead width to full bead separation (approximately 4.31 mm to 11.18 mm) at 0.77 mm intervals. The samples were sectioned and the deposit geometry was determined.

5.1.2 Third Bead-Placement Tests

This test was intended to evaluate the significance of accurate weld bead placement. The test involved the deposition of the third weld bead at a predetermined offset from the centre of two previously deposited beads. The spacing of the first two beads was one bead width (10.16 mm for horizontal and 7.62 mm for overhead) such that the two beads were just

touching. Third bead placement offset was 0, 1.27 or 2.54 mm from the centre of the two previously deposited beads. All tests were welded at an average current of 170A with the exception of vertical welds, which were welded at 110A.

5.1.3 Three-layer Weld Pad

A pyramid type three-layer weld test was used to examine the significance of bead placement on multi-layer welds. Horizontal and overhead weld test samples were performed with first layer bead spacings of 4.32 mm, 6.60 mm and 8.64 mm; weld beads in subsequent layers were deposited at the centre of two previously deposited beads.

5.2 Power Source Response Characteristics

Test plates with machined grooves at various depths were used to simulate sudden changes of arc length. Third bead placement tests were also performed with the Hobart Quantum and the OTC power supplies.

5.3 Welding Consumable Evaluation

S2 and S3 electrodes (triple and double deoxidized, respectively) were used to perform multi-bead tests under identical conditions of welding parameter selection and weld orientation.

5.4 Pulse Parameter Optimization

A limited amount of work was performed on the optimization of peak current and high pulse time using the OTC TRA 350 power supply. An oscilloscope was used to capture the current and voltage traces.

5.5 Welding Technique Development and Manual Procedure Testing

This is the most important phase of the project, where the findings from previous mechanized tests were applied to the development of a manually manipulated technique. Two welders from the Bruce Heavy Water Plant and one welding technician from the Research Division Welding Unit performed the welding trials. Groove welds were made in the horizontal (2G), vertical (3G), and overhead (4G) positions utilizing 9.5 mm and 25 mm thick plates. All-position (5G) pipe welding trials were performed using 200 mm diameter schedule 80 pipes. Figure 3 is a schematic for welding position terminology as specified by ASME.

6.0 RESULTS

6.1 Lack-of-Fusion Defect Simulation

6.1.1 Bead Spacing and Groove Geometry

Since the quality of a multi-layer weld may depend primarily on the nature of this surface, it is essential to establish the geometry of weld surfaces resulting from changes in interbead spacing. Bead-on-plate tests with progressive increases in bead spacing were performed in the horizontal, overhead and vertical welding positions. Figures 4a and 4b are cross-sections from horizontal and overhead test welds respectively. No lack-of-fusion defects were observed in either of the samples. With an average current of 170A and a travel speed of 6.35 mm/s, the single bead width of the horizontal weld is approximately 11 mm, while that of the overhead weld is 10 mm. Acceptable surface profile can be achieved by maintaining the spacing to less than 7.6 mm (0.300 in) for horizontal and 6.6 mm (0.260 in) for overhead. The best profile can be achieved by aiming the welding torch at the toe of the previously deposited bead.

Vertical welding was tested in the upward progression. It was found that a substantially lower average current (110A) has to be used to avoid weld pool drop-off when welding with the stringer technique. The tolerance for voltage fluctuation is also very narrow. Wetting on both side of the weld is poor when spacing is larger than 4.0 mm (0.157 in). Vertical-down welding was not thoroughly tested due to its inherent shallow penetration characteristics.

6.1.2 Third Bead Placement

Tests were performed in the horizontal, overhead and vertical-up positions. It was necessary to weld with offsets both above and below the centre-line during horizontal position welding. All tests were repeated to ensure reproducibility. Figures 5a and 5b are two typical examples of a horizontal test, which represent 0 and 2.54 mm (0.100 in) above offsets respectively. Lack-of-fusion defects were successfully simulated by welding with a 2.54 mm offset above the centre line in the horizontal welding position as shown in Figure 5b. This defect is similar in both appearance and orientation to those found during the temper-bead procedure qualification test, which was also welded in the horizontal position. No major fusion defects were found in samples welded in the overhead and vertical-up positions, but once again, welding vertical-up without weaving was found to be very difficult.

During repeatability testing of the third bead placement weld trials, a high percentage of weld starts were found to contain cold lap type fusion defects, as shown in Figure 6. This is especially prominent when welding in the horizontal position where the sagging of the weld pool is severe.

6.1.3 Three-layer Weld Pad

Cross-sections of two three-layer weld pad test specimens, representing 4.36 mm and 8.64 mm interbead spacings, are shown in Figures 7a and 7b. Placement of the second and third layer welds was determined by aiming at the weld bead intersects of the previous layer when scalloped surfaces were involved. No fusion defects were found in any of the samples.

6.2 Power Source Response Characteristics

Only a limited amount of work was performed using the Hobart Quantum 350 power supply due to frequent machine break down. Tests indicate that higher average current settings were necessary to obtain smooth transfer. It was also found that a stable arc can be maintained with a contact tip to workpiece distance (CT/WD) as long as 25 mm; the limiting factor seems to be the ability to ensure proper shielding when CT/WD becomes too large. Specially made plates containing several steps 3.18 mm (0.125 in) high were used to examine the response of the welding arc when an "up" or "down" step is encountered. It was observed that "stepping down" tends to create excessive buildup on the upper step, whereas the leading edge of the welding arc tends to melt the sharp edges of the step, thus creating a smoother transition, when welding in the "stepping up" progression. The Hobart power supply experienced a longer duration of arc instability than the OTC when steps were encountered. Cross sections of the test plates showed that the penetration depth of welds deposited by both power supplies during this test was relatively consistent even when the CT/WD varied by as much as 9.54 mm (0.375 in) during each run.

As expected, the penetration profile of the Hobart deposited weld has a more pronounced "finger". This is due to the selection of 95%Ar/5%O_2 rather than 80%Ar/20%CO_2 as the shielding gas.

Third bead placement tests conducted with the Hobart did not reveal significant improvement when bead misplacement is encountered. The tendency to trap cold lap type fusion defects still persisted when the third bead was offset at the 2.54 mm (0.100 in) above position.

6.3 Welding Consumable Evaluation

S2 and S3 welding electrodes (triple and double deoxidized respectively) were used to perform multi-bead tests under identical conditions of welding parameter selection and weld orientation. Visual inspection of the welds indicated less oxide buildup on the surface of the S3 welds compared to the S2 welds, especially along the toe of the weld beads. Oxide deposits were larger in size but fewer in number with the S3 tests, whereas numerous smaller areas of glass-like deposits were found associated with the S2 tests (Figure 8). Welding characteristics of the two wires are otherwise very similar.

6.4 Pulse Parameter Optimization

Since a substantial amount of development work has been performed by other researchers/7,8/, the focus of this work was to concentrate on the most promising possibilities, with limited in-house optimization of pulse parameters.

A digital storage oscilliscope was used to capture the wave form of the different power supplies. It was observed that the current and voltage traces of the OTC machines (Transistarc 350 and TRA 350) are trapezoidal rather than the theoretical square wave. The high pulse duration is substantially shorter than the 4ms established by other researchers, but the average high pulse duration is close to 4 ms when the slope up time is taken into account. It is very difficult to obtain an accurate current trace from the Hobart power supply due to the inherent high frequency characteristics of the machine. It was also determined that the OTC TRA350 possesses the most stable low current characteristics when compared to the other two power supplies; a stable arc can be maintained at an average current as low as 80A when welding with 0.9 mm diameter carbon steel wire. It was also found that increased arc stability can be obtained with the TRA350 by decreasing the high pulse current duration from the factory recommended 1.8 ms (F metting) to 1.4 ms (D setting).

6.5 Welding Technique Development and Manual Procedure Testing

6.5.1 Mechanized Groove Welds

Horizontal groove welds were performed utilizing 9.52 mm (3/8 in) thick carbon steel plates with a 75^{o} included angle weld preparation. Root passes were welded using the GTAW process since preliminary tests had indicated that a substantial amount of development work would be required to establish the parameters and technique for root pass welding using the P-GMAW process. Three layers of P-GMA welds, in addition to the GTAW root pass, were needed to fill the grooves. Single bead and two-bead second layer techniques were tested in both the horizontal and overhead positions. It was thought that the bridging of the wide weld groove with a single pass during second layer welding might produce side wall fusion defects, but no fusion defects were found in any of the samples (Figure 9).

6.5.2 Manual Groove Welds

Manually manipulated welding was performed with two different current settings. A low current/low travel speed setting (90 to 100A and 3.39 to 4.23 mm/s travel) was used in the first set of tests in the horizontal and vertical-up positions, in order to simulate conventional pipe welding conditions. A high current/high travel speed setting (160A and 6.77 mm/s travel), which was established as optimum during prior mechanized tests, was used in the second set of manual trials in the horizontal position.

Lack-of-fusion defects were found in both the stop and start areas and between fill passes of the test weld performed with the low current/low travel speed setting in the horizontal position. A typical cross-section revealing the stop and start defect is shown in Figure 10. No lack-of-fusion defects were found in the low current/travel vertical-up welds. Both full width weaving (Figure 11a) and the stringer technique (Figure 11b) were examined during vertical welding. Although no rejectable defects were found in specimens produced with either technique, it is apparent that the weaving technique is preferred due to superior side wall fusion characteristics and the ability to avoid the severe groove configuration experienced when using the stringer technique, as evidenced in the second layer welding shown in Figure 11b.

The high current/travel tests exhibited no rejectable defects. A 25 mm thick test plate was welded with the high current setting in the horizontal position. The stringer technique was employed, the optimum spacing rule (aim at the toe of the previously deposited pass) was also applied, and no lack-of-fusion defects were found (Figure 12).

6.5.3 Weld Start Technique Development

A series of weld start technique tests was conducted using the "step-back" technique usually used with the conventional GMAW process. Sectioning of the tests did not reveal any fusion defects. The only drawback with this technique is the excessive weld build-up at the start, which will require some degree of grinding in between passes.

6.5.4 Manual Pipe Welding Trials

Two maintainance welders from Bruce Heavy Water Plant were invited at different occasions to the Research Laboratory to perform all-position pipe welding trials. All the tests, with the exception of the final weld series, were conducted using the OTC Transistarc 350 power supply equipped with a Whiteman pistol grip style torch. The final procedure qualification tests were welded with the OTC TRA350 power supply. S3 wire 0.9 mm diameter was used in all tests.

The first set of runs was conducted by a welder who had previous experience with both conventional GMAW and P-GMAW. 2G and 4G position (Figure 3) groove weld tests were performed using 25 mm thick carbon steel plates at an average current of 160A utilizing the stringer technique. Several 6G position pipe weld tests were also performed using 203 mm (8 in) diameter 12 mm (1/2 in) thick SA333 carbon steel pipes. An average current of 100A and a full-weave technique were used all around the pipe joint. This low current level was selected mainly due to the limitations of welding in the vertical-up progression and the complexity of positional change when welding around the pipe. Some torch manipulation difficulties were encountered by the welder due to the rigidity of the Whiteman welding torch. All test specimens were radiographed, and found acceptable in

accordance with ASME Section III standards/9/. Cross-sections of the plate welds revealed no rejectable indications, but some lack-of-fusion defects were found in cross-sections cut from the 12 o'clock position of the pipe weld. Additional welding tests confirmed that weaving at the 12 o'clock position of a 6G oriented pipe emulates the vertical up and down welding progressions, and the chances of producing lack-of-fusion defects when travelling during the down progression is very high.

Another pipe welder who had no prior experience with the GMAW process was invited to OHRD to perform a pipe welding procedure qualification test using the P-GMAW process. The welder was given three days of training prior to testing. It was also during this period that the welding machine was "acting up", which resulted in excessive spattering; it was later found that the gas mixer was faulty. Test coupons on a 19 mm plate (2G position, 160A) and a 200 mm diameter Sch 80 pipe (5G position, 100A) were produced. Ultrasonic and radiographic examinations were performed on both test pieces. The plate sample was found acceptable, but the pipe test was rejected due to gross lack-of-fusion and porosity defects.

The second attempt for procedure qualification was conducted at the Bruce Heavy Water Plant using the first welder. It is worth noting that the welding torch used in this series of tests was a water-cooled OTC "goose neck" style torch, which is substantially lighter and more flexible than the Whiteman torch. 200 mm diameter Sch 80 pipe weld coupons were used throughout the tests. All tests were welded with an average current of 110A. Both stringer and full weave techniques were tested for the second layer. The "step-back" technique was used for all weld starts, and the stop areas were all ground prior to deposit of the next pass. Figure 13 shows a large fusion defect in the cross-section of a weld utilizing the stringer technique for the second layer. Figure 14 is a cross-section of a weld made with the full width weaving technique, in which no rejectable defects were found. Two test coupons were examined using radiographic and ultrasonic techniques, and both were found acceptable in accordance with ASME standards/9/. This welding procedure has been tested and registered with the regulatory agency.

7.0 DISCUSSION

7.1 Lack-of-Fusion Simulation

It is very important to have a clear understanding of the causes of lack-of-fusion defects, such that solutions can be developed to avoid their occurrence. It is well known that only a small percentage (about 20%) of the total energy of the welding arc goes into base metal melting, and the width of the arc is very narrow when compared to the total width of the weld bead. The result is the characteristic "finger" type penetration, with little or no secondary penetration, especially at the weld toes. The ability to produce lack-of-fusion defects in the horizontal welding position, by a combination of wide bead spacing and bead placement, has

established that the tolerance for weld bead misplacement could be very small when welding on a surface containing weld beads which are poorly spaced and produce a certain weld groove geometry. These defects are probably caused by cold lap of the weld metal; the heat of the arc is concentrated at the upper edge of the groove, thus creating a cold-lap defect when the weld bead "rolls over" due to gravity and covers the lower edge of the weld groove. The fact that these defects are similar in both size and orientation to those encountered during previous temper-bead welding procedure qualification trials further enhances the significance of this observation. The proper way to minimize the occurrence of cold-lap type lack-of-fusion defects when welding in the horizontal position, is to control the surface geometry of the prior deposited layer rather than controlling bead misplacement. In other words, it is essential to prevent the occurrence of deep and/or wide grooves between weld beads. Bead spacing tests have shown that an acceptable weld surfaces geometry can be achieved by maintaining a bead spacing from 4.3 to 7.6 mm when welding in the horizontal position, and 4.0 mm to 6.6 mm when welding in the overhead position. The rule of thumb is to aim at the toe of the previous bead in order to obtain optimum surface profile. This critical geometry and misplacement combination is mostly likely only applicable to 160A/6.35 mm/s current/travel speed settings. Lower current settings will probably result in a shallower penetration profile, thus increasing the chances of fusion defects occurring. It has also been established that weaving is necessary when welding in the vertical-up progression.

Since no lack-of-fusion defects were found in the three-layer weld pad tests, it is very likely that critical groove geometry and misplacement must both be present in order to reproduce the cold-lap type fusion defect. Although a full bead separation condition was encountered during testing (Figure 7b), the accurate bead placement at the centre of the resulting interbead groove, and use of a mechanized travel system virtually eliminated the chances of creating the expected defects. This should not apply to manual welding since it is almost impossible to expect a welder to be able to accurately track the centre of the groove to within a 2.54 mm (0.100 in) tolerance.

7.2 Welding Equipment and Consumables

Third bead placement tests have proved that the synergic characteristics of the Hobart power supply cannot significantly improve the tolerance for weld bead misplacement. No attempt has been made to evaluate the difference between synergic control and frequency-modulated power supplies when full weave technique is employed. It is possible that the rapid change in arc length, during manual manipulation of the arc from the centre of the weld groove to the side walls, will result in a periodic decrease in pulse frequency when the frequency-modulated OTC power supply is used, this in turn will decrease the heat input due to the associated increase in low pulse duration. On the other hand, the synergic design will maintain the heat input during arc length fluctuation, by varying all the variables (I_p,

I_b, T_p and T_b). This point is very difficult to verify since no major defects were encountered during manual weld tests performed with the weaving technique using the OTC power supplies.

The OTC TRA 350 power supply was preferred over the Hobart Quantum and the OTC Transistarc 350 due to its ability to maintain a stable transfer at low current settings; this feature is most important during all-position pipe welding, where the low current level is necessary for welding in the vertical-up progression. The other attractive feature with the OTC TRA350 is the ability to make adjustments to the pulse variables to fine tune the welding arc performance for specific applications. In this case, it was found that a shorter than factory recommended high pulse duration is preferred for low current welding.

It was also found that the welding torch design will have a significant effect on the quality of the weld. It is necessary to adjust the welding torch angle continuously when welding around a pipe. It is thus very important to have a torch that is both well balanced and flexible, such that the manouverability of the torch around the pipe joint will not be hindered. The relatively high peak current used for the P-GMAW process demands a water-cooled welding torch. The combination of the shielding gas line, water lines and the heavy power cable usually make the connecting cable heavy and cumbersome. The addition of a steel spring protection at the torch body and cable junction, as in the case of the Hobart factory-supplied torch, will make manipulation impossible for pipe welding applications. The "goose neck" style torch is preferred over the pistol grip type, due to improved handling ability. The goose neck design also increases the distance between the hand and the arc, which results in increased operator comfort.

Although any direct link between wire composition and defect formation has not been unambiguously established, it is concluded that S3 should be the welding wire of choice due to the reduced tendency for slag formation, as well as the higher impact properties found with this wire in previous tests/10/. It was also decided that 85%Ar/15%CO_2 should be used due to lower spattering characteristics, while penetration geometry remains very comparable to that of the recommended 80%Ar/20%CO_2 shielding gas mixture.

7.3 Welding Technique Development and Procedure Qualification

It has been proven that acceptable groove welds in plate can easily be produced by following the optimum bead spacing criteria and using a high average current setting (140-160A), in both the overhead and horizontal welding positions. This is mainly due to the ideal surface profile resulting from proper weld bead spacing, and the penetration from the high heat input. Unfortunately, this is not applicable to all-position manual pipe welding. The continuous readjustment of welding torch angle, and the requirement to weld the majority of the joint in the vertical position, necessitates the use of low current settings (100-110A) to give the welder

a more controllable process. It has been established that although a stable transfer can be maintained with current settings as low as 90A, a minimum of 110A should be used to obtain sufficient penetration.

As proven in the mechanized tests, weaving must be employed when welding in the vertical-up progression. The weave motion not only improves weld deposit surface geometry, it also increases the width of the primary penetration by moving the arc transversely across the linear travel direction. Figure 15 shows the improved penetration profile resulting from weaving. Penetration depth is very similar to that of the stringer bead (Figure 15a), but the secondary penetration is increased substantially (Figure 15b).

Judging from the results of the pipe tests welded with the stringer technique, it is necessary to weave the first few layers until the width of the groove is wide enough to accept multiple stringers. Even then, extreme care must be taken to avoid excessive weld bead "roll over". It was found that full width weaving (up to 25 mm wide during the capping pass) can be performed without difficulties. "Split pass" capping was examined during one welding trial, in an attempt to minimize weld reinforcement height especially at the overhead position. It was found that the reinforcement height did not decrease when the weave width was reduced from 25 mm to 12 mm; this is in good agreement with a previous observation, made during the development of a welding procedure for robotic applications with stainless steel/3/, that the weld deposit reinforcement is relatively insensitive to reasonable welding heat input fluctuations.

Since pipe welding tests have only been conducted on 12 mm thick pipes, no weaving of wider than 25 mm has been tested. Thus the maximum limit for full width weaving is still not known. It is likely that split pass weaving is necessary when thicker welds are involved. The ability to weld with a narrower groove configuration has also not yet been examined, and is likely to be essential when the fabrication of thick wall piping is involved.

The lack-of-fusion problem at the weld start is most likely caused by cold lapping due to the unstable condition of the weld pool during arc initiation. This problem was eliminated by minor grinding and practicing the "step back" technique.

Like any other welding process, the skill level required to produce acceptable welds is very high and, judging from the test results of the two welders, it is certain that welder training is extremely important. It is essential for the welder to understand the characteristics and the limitations of the process prior to hands-on training. A proposed P-GMA welder training program is shown in Appendix 1.

Very little work was done on root pass welding with the P-GMAW process. It is anticipated that the development of an open root welding procedure using this process will be difficult. Initial tests have shown substantial amounts of weld metal loss through the open root gap. It is also expected that the acceptance of root pass welding using other than the GTAW process for nuclear applications will not be easy.

8.0 CONCLUSIONS

A detailed development program has been conducted to determine the possible causes of lack-of-fusion defects found in previous procedure qualification tests using the P-GMAW process, and to establish suitable welding techniques to obtain high integrity manual plate and pipe out-of-position welds. Several important factors have been examined. Principal findings are:

8.1 Lack-of-fusion defects similar to those found in previous qualification tests can be simulated by a combination of bead spacing and bead placement, while welding in the horizontal position. They are believed to be associated with the inherent "finger"-type penetration characteristics of the GMAW process.

8.2 The easiest method to combat fusion defects is to avoid the occurrence of deep and/or wide grooves between weld beads, by proper weld bead placement. The recommended technique to obtain optimum surface profile is to aim at the toe of the previous deposited bead.

8.3 No significant difference in fusion characteristics was found between the frequency-modulated OTC power supplies and the "synergic" control Hobart Quantum 350 power supply.

8.4 The ER70S-3 welding consumable has been chosen due to superior weld metal properties and less slag formation. An 85%Ar/15%CO_2 shielding gas composition was selected due to its low spatter characteristics.

8.5 Radiographic and ultrasonic quality welds can easily be produced using the stringer technique and an average current between 140 to 160A.However, the high current setting tends to make all-position pipe welding impossible.

8.6 A weaving technique has to be employed for all-position pipe welding or when the vertical-up progression is involved, using a minimum average current of 110A.

8.7 The "step back" technique has to be used during weld starts in order to avoid fusion defects.

8.8 Appropriate welder training has proven to be one of the most important requirements for obtaining high quality pipe welds.

8.9 A manual all-position pipe welding procedure has been qualified, and is avaialble for use in Ontario Hydro.

8.10 Further investigation is required to establish process parameters and welding techniques for heavy wall pipe welding, and for P-GMA root pass welding.

ACKNOWLEDGEMENTS

The author wishes to thank Mr. R.W. Hopkins of the Welding Unit for his excellent technical support. Mr. B. Jennings and Mr. K. Russell of BHWP performed manual pipe tests. Mr J. Hare and Mr. D. Farmery, who were work-term students from Northern College and Mohawk College respectively, performed the metallography, and CNS provided funding support. Thanks are also due to Mr. M.J. Tinkler, Mr. L.F. Robertson, and Mr. J.W. Prince for their helpful discussions, and to Mr. Tinkler, for his help in the preparation of this report.

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APPENDIX 1

P-GMA OPERATOR TRAINING PROGRAM(DURATION 2 WEEKS

R.W. Hopkins

The purpose of the training period is to familiarize an operator with the Pulsed Gas Metal Arc (P-GMA) welding process. This program should develop a sufficient level of skill to enable this operator to manually weld plate and pipe in all positions and to code requirements, if warranted.

The program should be tentatively scheduled as follows:

Day 1: Theory of the P-GMA process, its operating peculiarities and where the operator has previous GMA welding experience, the differences between pulsed and non-pulsing systems should be covered.

Hands-on familiarization with the equipment.

Bead-on-plate exercises with varying power settings and travel speeds to develop the technique required to produce acceptable bead width, contour, wetting etc.

Day 2: Development of techniques of correct bead spacing, wash-up and multilayer welding in the flat position.

Repeat of above in the horizontal position.

Day 3: Repeat of above in overhead position.

Vertical-up beads. Since vertical-up has proven to be the least forgiving of all positions of P-GMA welding the operator needs to develop the low power weave technique necessitated by the process limitations.

Day 4: Assuming the foregoing exercises are successful, it should be possible to produce a multipass groove weld in plate on the fourth day. To further concentrate the training period, it is felt that this test plate should be welded in the horizontal mode rather than in the flat (downhand).

Day 5: While assessment (NDE, metallography, etc) of the day 4 plate is being performed, the operator should shift his efforts to the welding of pipe utilizing the knowledge gained from the previous four days.

Days 6 to 10: An attempt should be made at this time to produce a representative, though not necessarily a formal, pipe sample, welded in the 5C position. Evaluation of this sample coupled with the foregoing work should indicate the feasibility of producing a formal (as per MCCR requirements) test coupon.

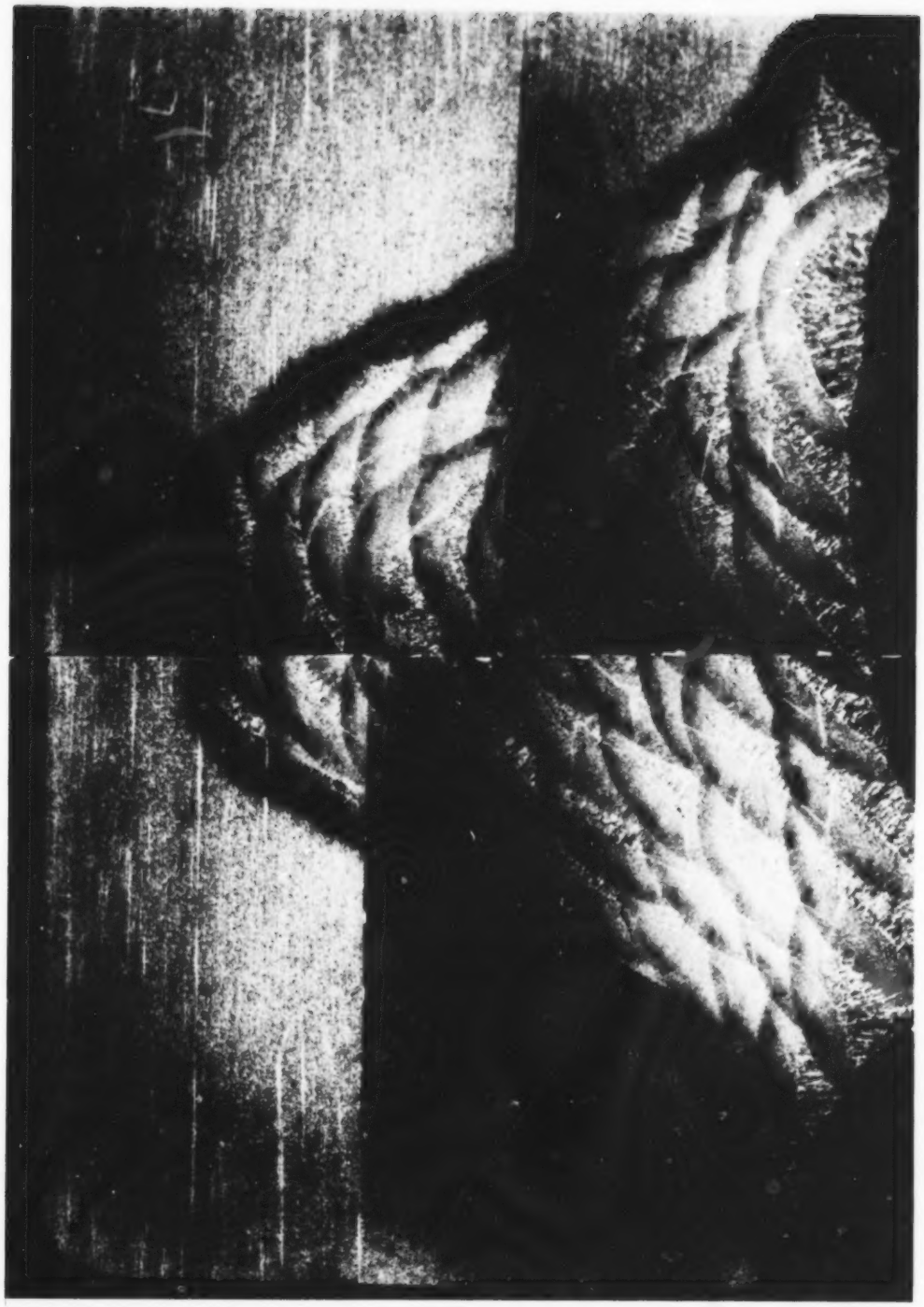


FIGURE 1

P-GMAW TEMPER BEAD REPAIR COUPON 3x
(NOTE LACK-OF-FUSION DEFECTS)

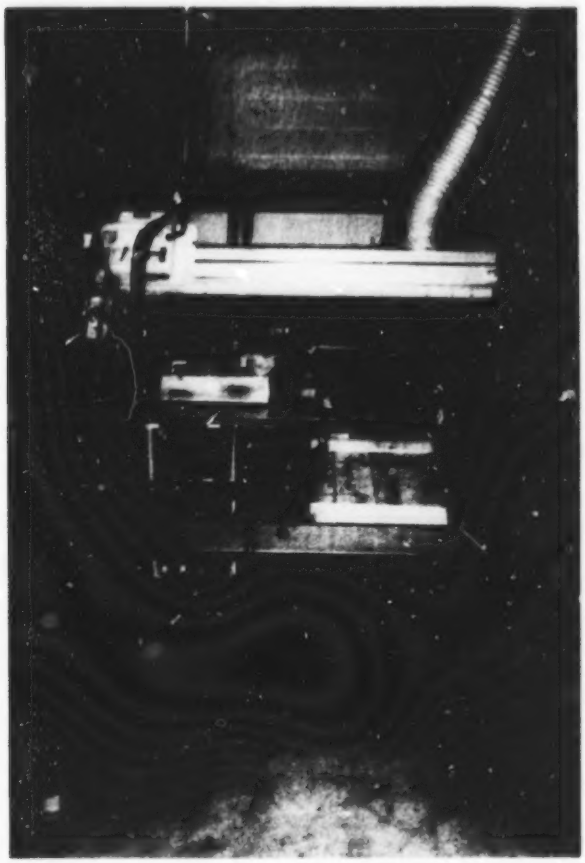
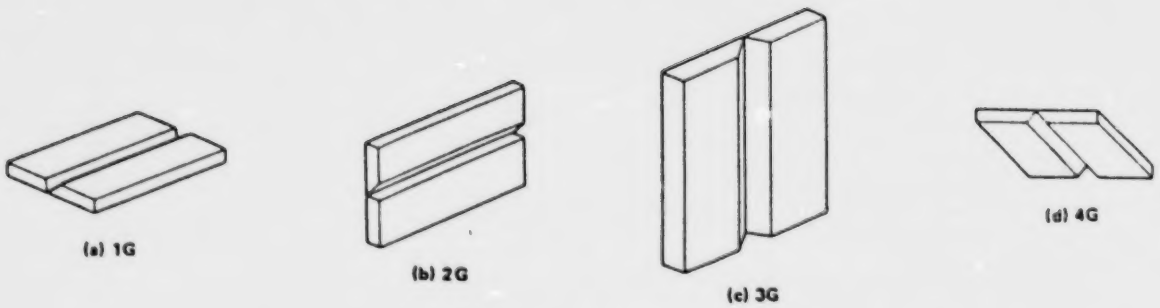
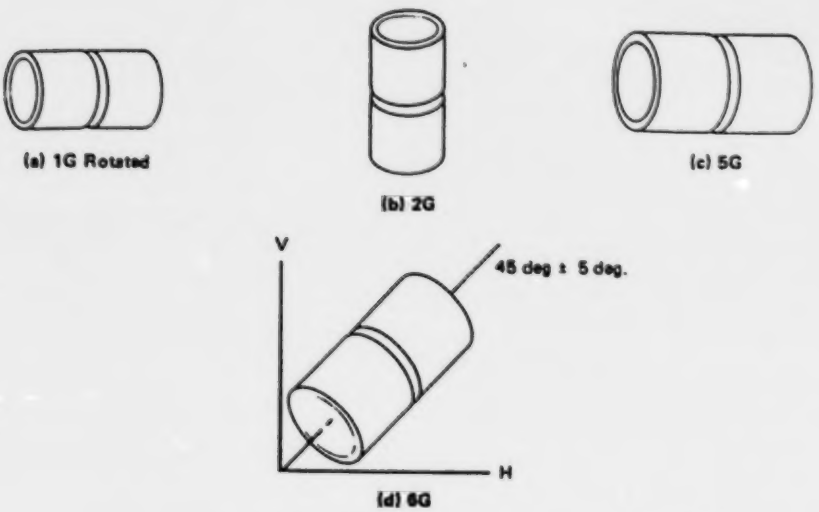


FIGURE 2
ALL-POSITION FIXTURE FOR WELD TEST PROGRAM



GROOVE WELDS IN PLATE — TEST POSITIONS



GROOVE WELDS IN PIPE — TEST POSITIONS

FIGURE 3

WELDING POSITIONS AS STIPULATED
BY ASME (COPY FROM ASME SECTION IX)

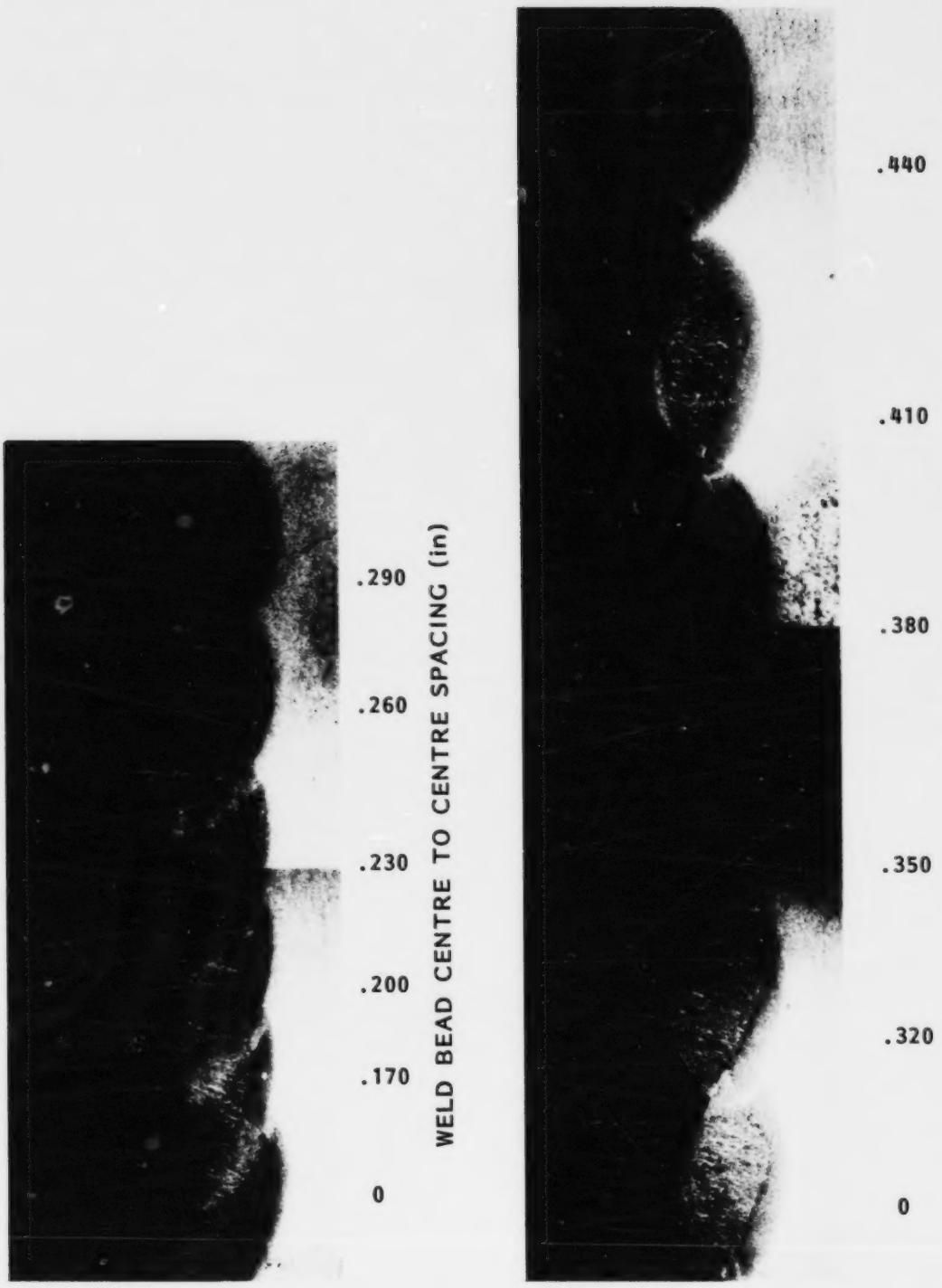


FIGURE 4a
BEAD SPACING TEST (HORIZONTAL), x 3

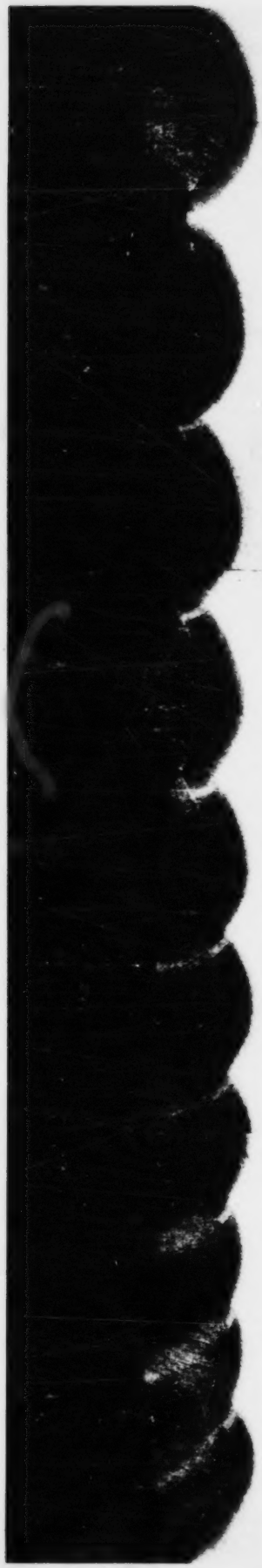


FIGURE 4b

BEAD SPACING TEST
(OVERHEAD), x 3.5

176380-RD

FIGURE 5a

THIRD BEAD PLACEMENT TEST
0 OFFSET

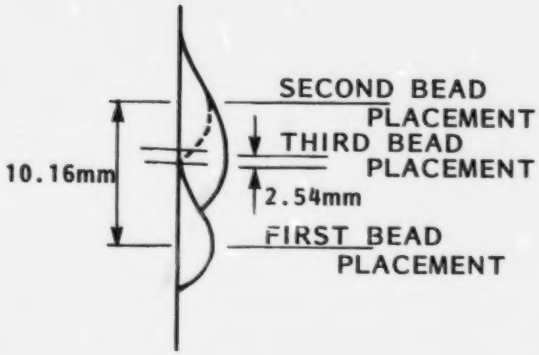


FIGURE 5b

THIRD BEAD PLACEMENT,
2.54mm OFFSET (HORIZONTAL) x 4

176382-RD

FIGURE 6
WELD START DEFECTS

176383-RD

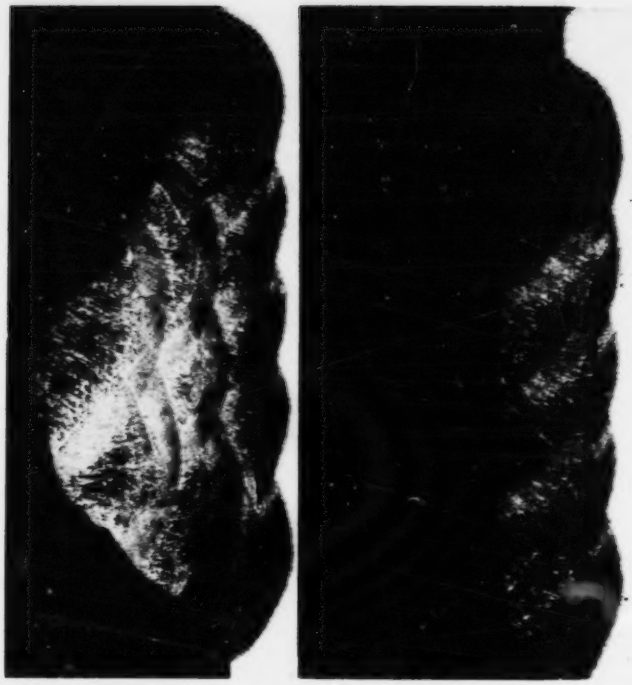


FIGURE 7a

THREE LAYER WELD PAD,
4.3mm SPACING, x 3.5

FIGURE 7b

THREE LAYER WELD PAD,
8.6mm SPACING, x 3.5

176384-RD

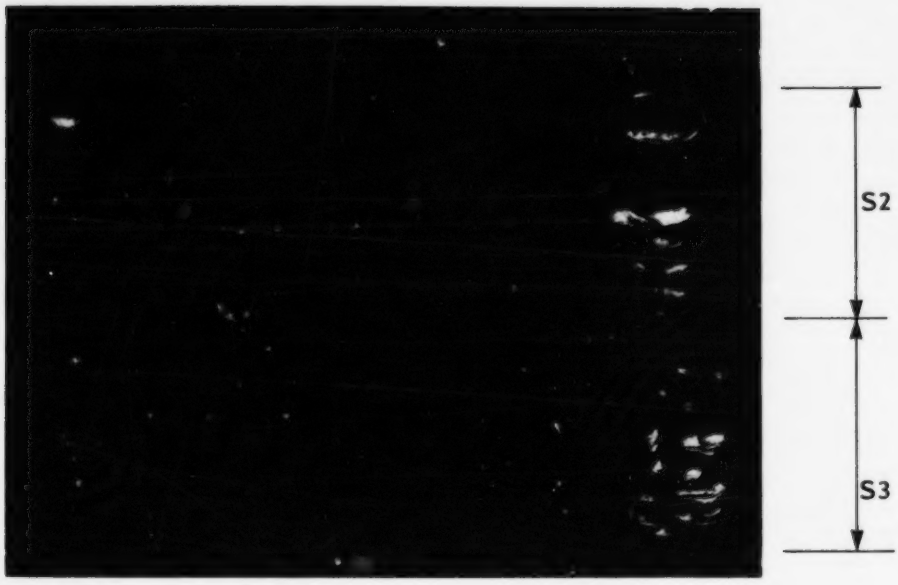
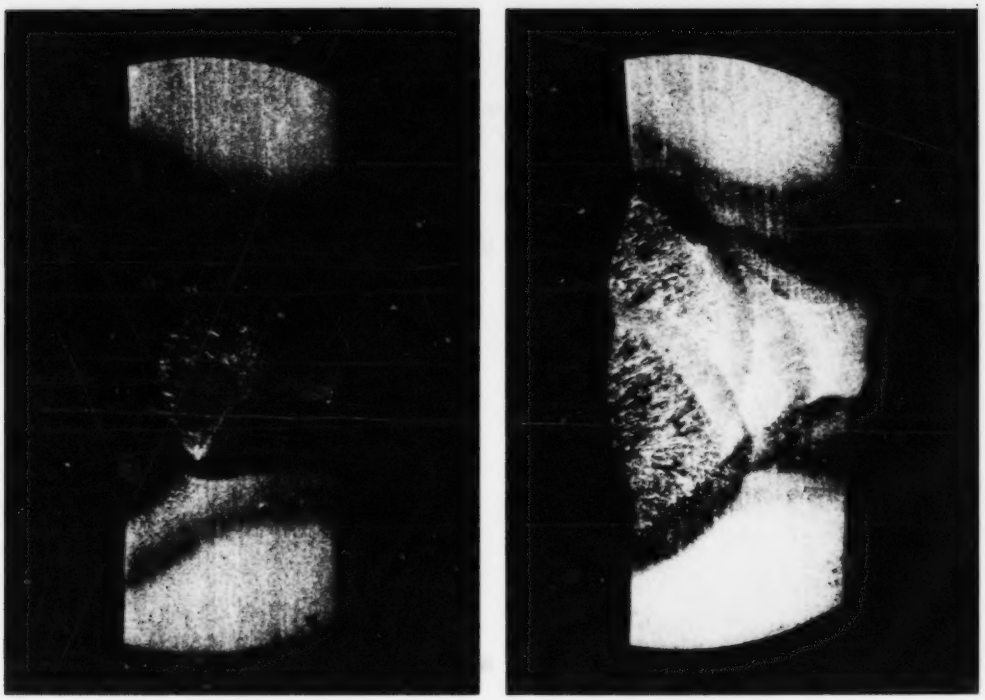


FIGURE 8

COMPARISON OF WELD BEAD SURFACE APPEARANCE
FOR TWO WIRE TYPES (E70S2 VS E70S3)

176385-RD



SECOND LAYER FOURTH LAYER

FIGURE 9

MECHANIZED GROOVE WELD
(HORIZONTAL), x 3.5

176386-RD

FIGURE 10

LACK-OF-FUSION DEFECTS AT THE WELD START,
x 6.67 (100A/4.22mm/s, HORIZONTAL)

176387-RD

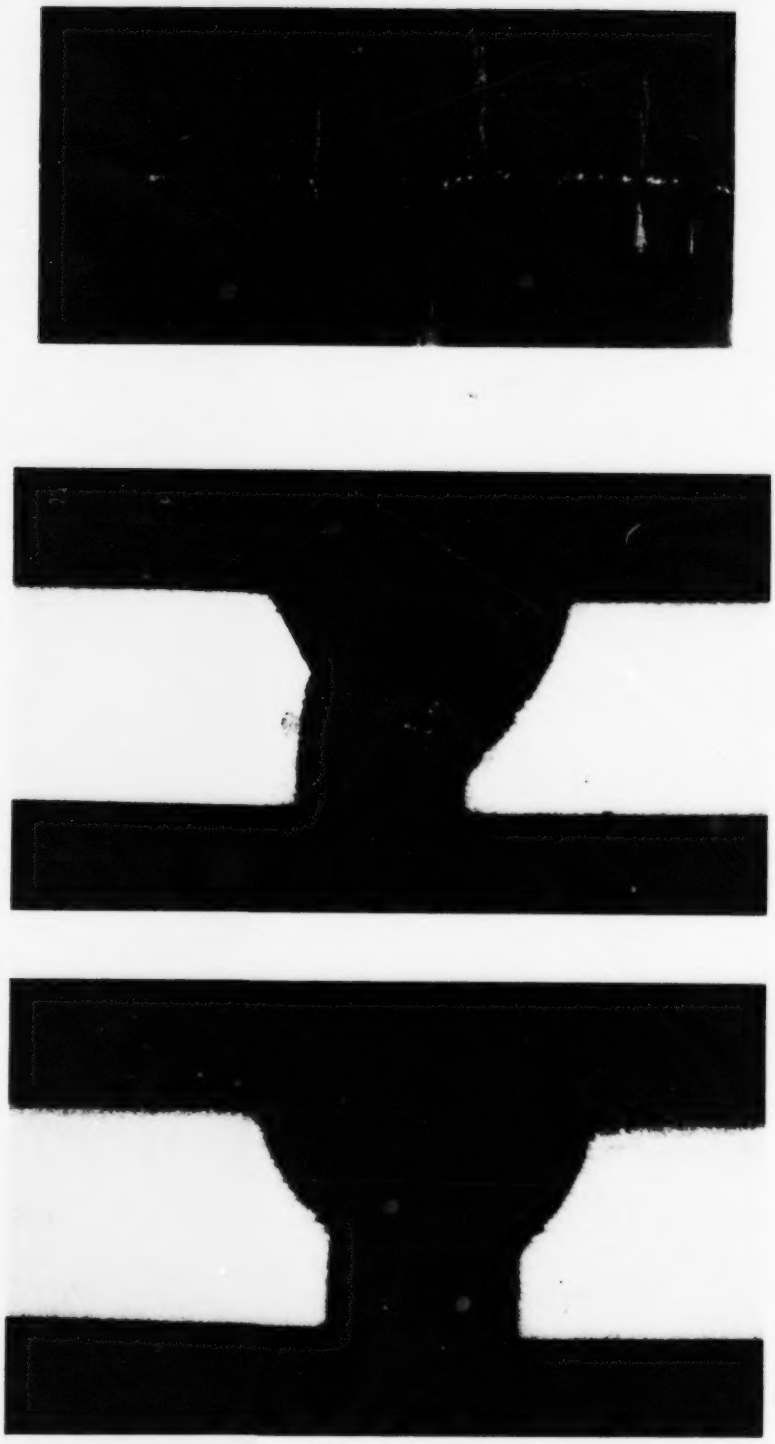


FIGURE 11a

VERTICAL-UP MANUAL GROOVE
WELD, STRINGER TECHNIQUE

176388-RD

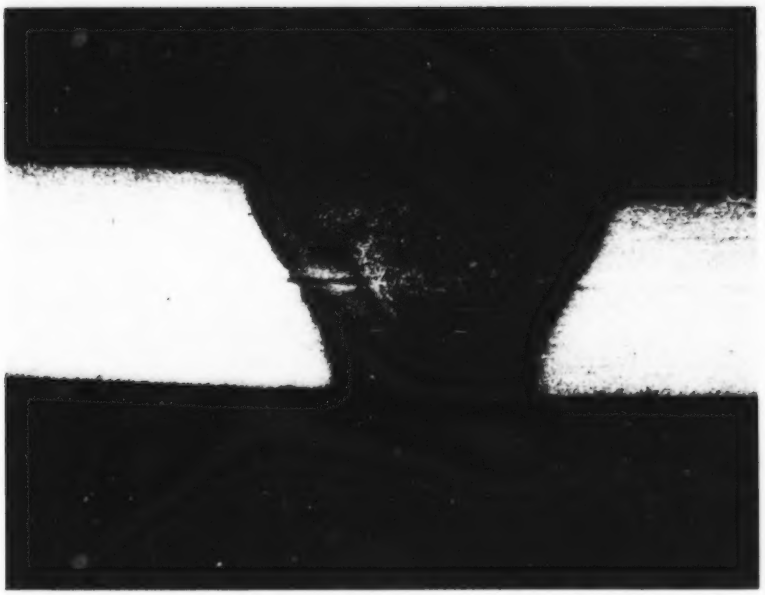


FIGURE 11b

VERTICAL-UP GROOVE WELD,
x 3.5 (100A/3.4mm/s)

176389-RD

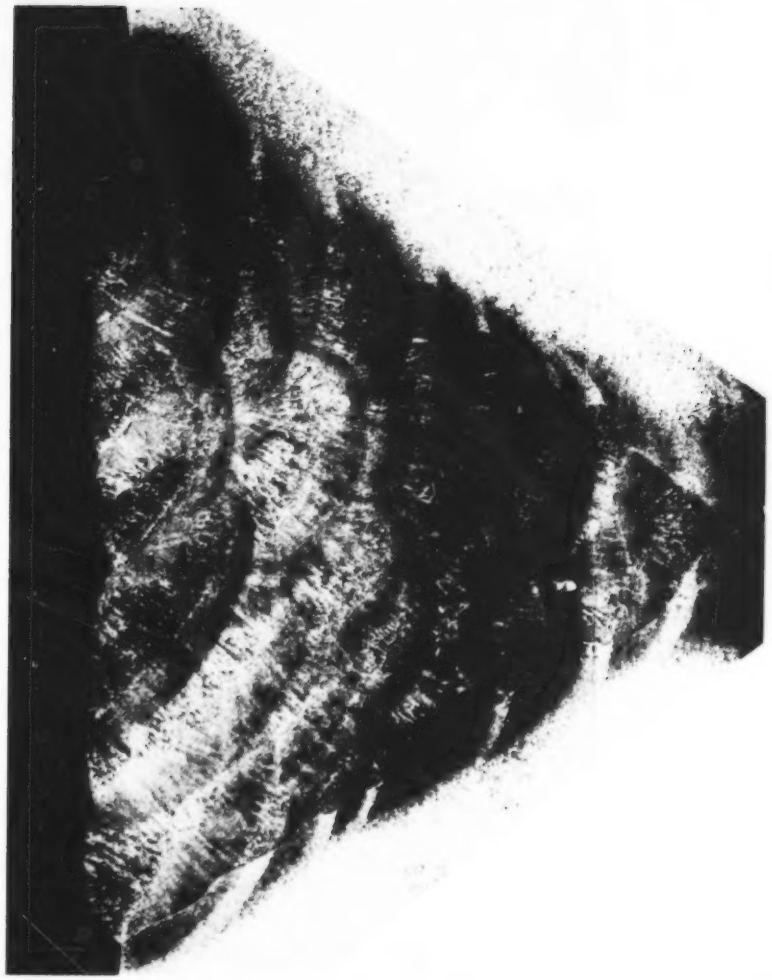


FIGURE 12

HORIZONTAL GROOVE WELD, 25mm PLATE AT
160A/6.8mm/s, x 3.5

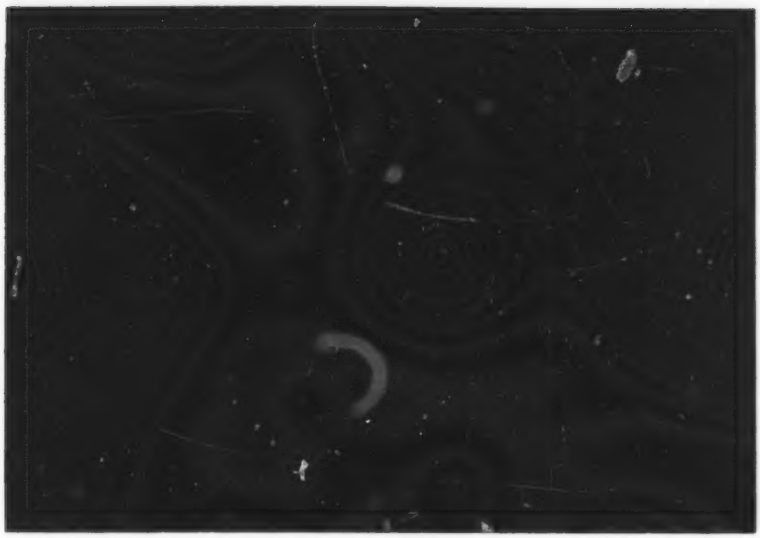
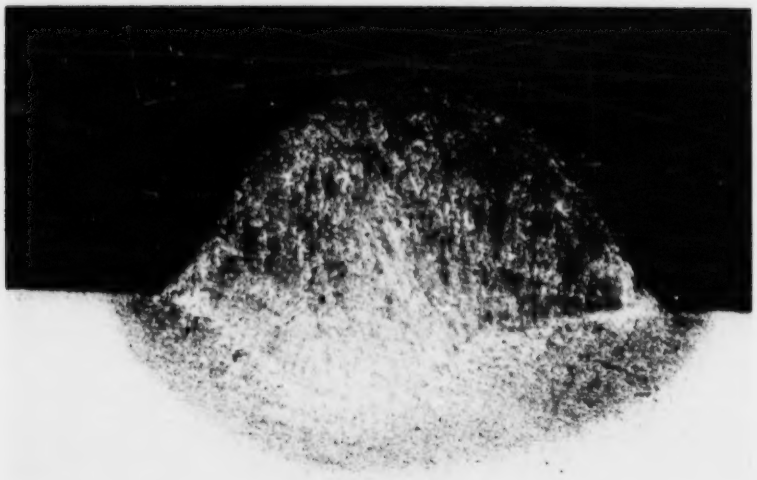


FIGURE 13

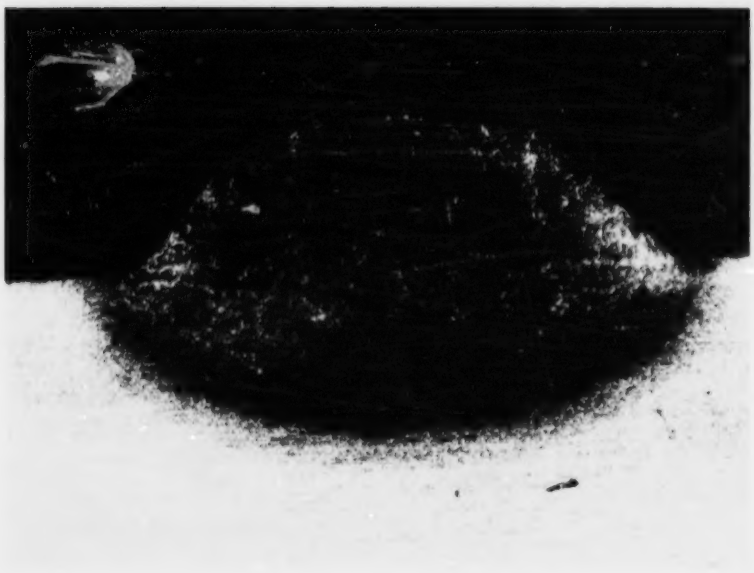
MANUAL PIPE WELD
(STRINGER TECHNIQUE, 2nd LAYER)

FIGURE 14

MANUAL PIPE WELD
(FULL WEAVE TECHNIQUE)



15a STRINGER TECHNIQUE
(120A, 0 WEAVE)



15b WEAVE TECHNIQUE
(120A, 4 mm WEAVE)

FIGURE 15
EFFECTS OF WEAVING (BEAD-ON-PLATE)